DTU Library

Measuring the spatial structure of turbulence

Courtney, Michael

Published in:
Meteorology and Wind Energy Department. Annual Progress Report. 1 January - 31 December 1987

Publication date:
1988

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Courtney, M. (1988). Measuring the spatial structure of turbulence. In *Meteorology and Wind Energy Department. Annual Progress Report. 1 January - 31 December 1987* (pp. 45-57). Risø National Laboratory. Denmark. Forskningscenter Risoe. Risoe-R No. 560

Risø–R–560

METEOROLOGY AND WIND ENERGY DEPARTMENT ANNUAL PROGRESS REPORT

1 January – 31 December 1987

edited by E.L. Petersen and B. Skrumsager

Abstract. The research in the Department of Meteorology and Wind Energy is directed towards two major applications: wind energy and modelling air pollution dispersion. In order to maintain a high level of technical competence within these applications, the department has carried out both theoretical and experimental basic studies. The subjects range from surface energy balance research of the general spatial and temporal structure of atmospheric turbulence to wind engineering investigations of dynamic loads on buildings, bridges, and other structures. Very important parts of the applied work are the testing and licensing of wind turbines for the Danish market and providing consultative services for Danish wind turbine manufacturers.

May 1988

Risø National Laboratory, DK–4000, Roskilde, Denmark

ISBN-87-550-1419-4
ISSN 0106-2840
ISSN 0903-9627

Grafisk Service, Risø, 1988.

Contents

3 Measuring the spatial structure of turbulence

Michael Courtney

3.1 Introduction

It is now widely appreciated that the turbulence of the wind can have a highly deleterious effect on a rotor's fatigue life. Furthermore, the power quality of a wind turbine is highly dependent on the turbulent content of the impinging wind. In order to model these phenomena it is clearly essential to have the best possible description of the wind.

Much effort has been expended in obtaining, analysing and characterising the temporal structure of wind. Typically this information is presented in the form of a spectrum of velocity fluctuations at a fixed point, as measured by a cup anemometer. A description of the wind field over the entire rotor disc is incomplete without a representation of the spatial structure. This would be given by cross-spectra for every pair of points in the rotor disc. An equivalent and more convenient form is to use coherence and phase functions, in which the displacement between two points enters explicitly. Comparatively little attention has been given to assessing the applicability of existing coherence models with regard to wind turbines. The work described in this paper is aimed at redressing this.

Current practice
For the calculation of turbulence induced loads on a wind turbine rotor, it is sufficient only to include the longitudinal (u) component of turbulence (Jensen and Frandsen, 1978). Thus we are interested only in the lateral coherence between the u components of turbulence, of any two points in the rotor disc.

Whilst for most building structures, one dimension predominates (horizontal for a suspension bridge, vertical for a tower block), for a wind turbine both lateral dimensions are equally important. Thus we are concerned not with purely horizontal or vertical separations but with the coherence of any two points in a vertical plane perpendicular to the mean wind. Most existing models and data sets deal with coherence in one lateral direction only.

Existing wind engineering practice, after Davenport (1961) is to model the lateral coherence of points separated vertically as an exponential function of a dimensionless parameter $\frac{fD}{U}$, namely

$$COH(\frac{fD}{U}) = e^{-a_z \frac{fD}{U}}$$

where f is frequency, D the lateral separation of the two points and U the mean wind speed, all parameters being in consistent units. The decay constant a_z is typically taken as 14 in neutral stratification.

A certain ambiguity exists as to the choice of the mean wind speed U, since for vertical separations the values at the two points will generally be different. Whilst some workers take a reference velocity at 10-m height, it is more common to take a mean of the two mean speeds. This is the practice adopted throughout this work.

That the coherence reduces to a function of a single parameter including frequency, displacement and mean wind speed, is extremely convenient. This is commonly referred to as Davenport similarity, since, according to Taylor's hypothesis, the parameter may be interpreted as the ratio of separation to wavelength, the coherence depending only on this quantity.

Unfortunately, the decay constant a_z is found to vary greatly with atmospheric stability. In high winds (neutral stability) a_z is also found to be a function of height. For horizontal separations, the same exponential function is commonly used with a_z replaced by a corresponding constant a_y. Once more, corrections have to be applied to the decay constant to account for height, separation and stability: see Panofsky and Dutton (1984).

Application to wind turbines
For the calculation of turbulence-induced loads on a stationary rotor, the Davenport coherence model may be used, for example Madsen (1986). One is faced, however, with the difficulty of choosing a decay constant, since generally different values are found for horizontal and vertical separations. No data exist for orientations between these two extremes.

An additional complication faced in the calculation of loads on an operating wind turbine is that the auto- and cross-spectra are modified by the effects of rotation, energy from lower frequencies being shifted to harmonics of the rotational speed. In the analysis of Kristensen and Frandsen (1982), the auto- and cross-spectra are derived directly for the rotating frame, using a model based on isotropic turbulence and the application of Taylor's frozen turbulence hypothesis. This approach forms the basis of most frequency domain turbulence analyses, for example Madsen et al. (1984), Garrad and Hassan (1986).

In an earlier theoretical model proposed by Kristensen and Jensen (1979), fundamentally the same assumptions are employed to derive a model of lateral coherence in the stationary frame. Results for all four non-zero coherence functions are given.

Lacking simultaneous time series for points with vertical, horizontal and skew separations, an assessment of the applicability of the available models to wind turbines was not previously possible. The Lammefjord experiment was initiated in order to provide such a data set.

3.2 Description of the first experiment

Site selection
A site was sought that would give homogeneous wind from the prevailing direction. Whilst Denmark is relatively low lying, most of the country is gently undulating. However, on the island of Zealand, some 50 km from Risø, there is an area of land reclaimed from a shallow, flat bottomed fjord. The light, sandy soil makes the area suitable for agriculture, in particular the growing of root crops such as carrots and potatoes. This results in a low and generally uniform surface roughness. Since most of the buildings are grouped together on the areas previously above water, it was possible to find a site giving a 3-km fetch, both flat and completely free of obstacles larger than a telegraph pole.

Measuring equipment
Three masts were erected in a plane perpendicular to the prevailing south-westerly wind. A total of 16 fast responding cup anemometers were mounted on the masts, in a pattern giving the best possible spatial resolution (Fig. 10). The array essentially covers a plane 30 m $\times$ 30 m, corresponding to the rotor disc of a medium sized wind turbine. Two wind direction vanes, each providing a sine and cosine signal, were also mounted. After installation, the positional accuracy of the array was measured and found to be within 2 cm.

Data were recorded on a 22-channel FM tape recorder, giving a recording duration of approximately nine hours on one tape. Power for the tape recorder and for the signal conditioners for each instrument, was provided by a mobile 220-V generator.

A second, climatological system was also installed on the masts. This comprised temperature sensors at three heights (giving direct absolute and difference measurements), pressure, humidity and energy flux sensors. Observations were taken every 10 minutes and recorded using a battery powered, CMOS memory pack. This system has been in continuous operation from the spring of 1986.

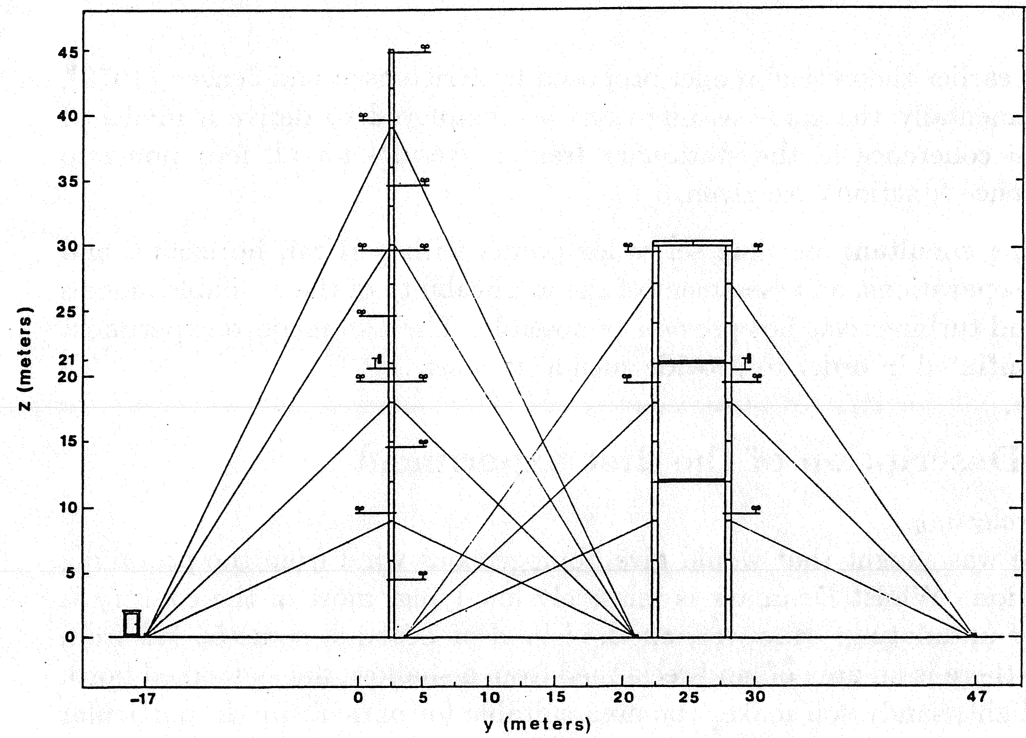

Figure 10: Mast layout for the first experiment

3.3 Results from the first experiment

In the first instance, data were required for medium to high wind speeds, corresponding to neutral stability. Since it was clearly impossible to yaw the mast array, the recording strategy was simply to wait for south-westerly wind of sufficient strength. When these conditions occured, data were recorded for as long as the wind prevailed. In this manner, approximately 60 hours of data were obtained, mostly in the month of November 1986.

Each data set was digitized at 5 Hz and transferred to a mainframe computer. Ten-minute statistics were calculated for each time series in order to identify that most suitable for spectral analysis. Coherence is defined as the limit of the coherence function as the statistical degrees of freedom tend to infinity. By implication, the longest time series possible should be chosen. However, it is also important to ensure that conditions remain sensibly constant throughout the time series, particularly the wind direction. Reconciling these two criteria, a time series of approximately seven hours duration, possessing unusually constant wind direction, was chosen. From this data set, ten minute means and standard deviations, for a cup anemometer at 10-m height, are shown in Fig. 11. Means for the wind direction for the same period are given in Fig. 12.

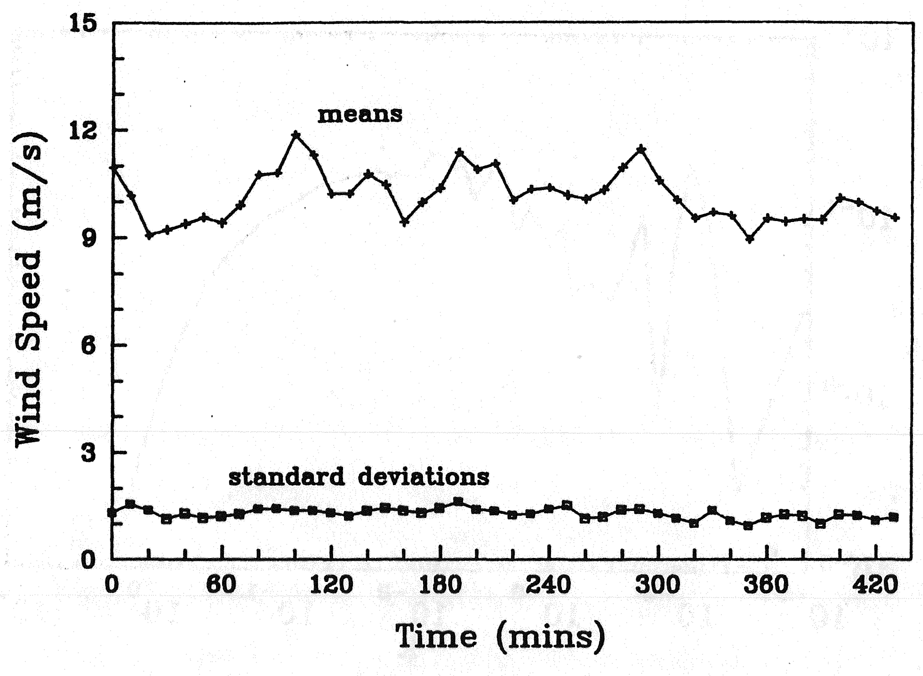

Figure 11: Ten-minute wind speed statistics at 10 m.

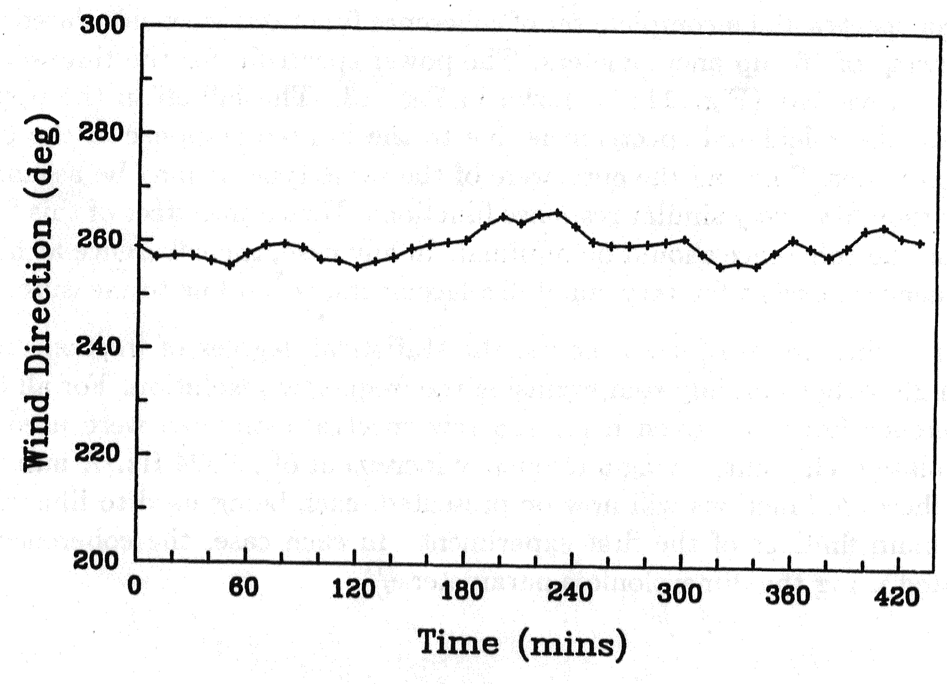

Figure 12: Ten-minute mean wind directions.

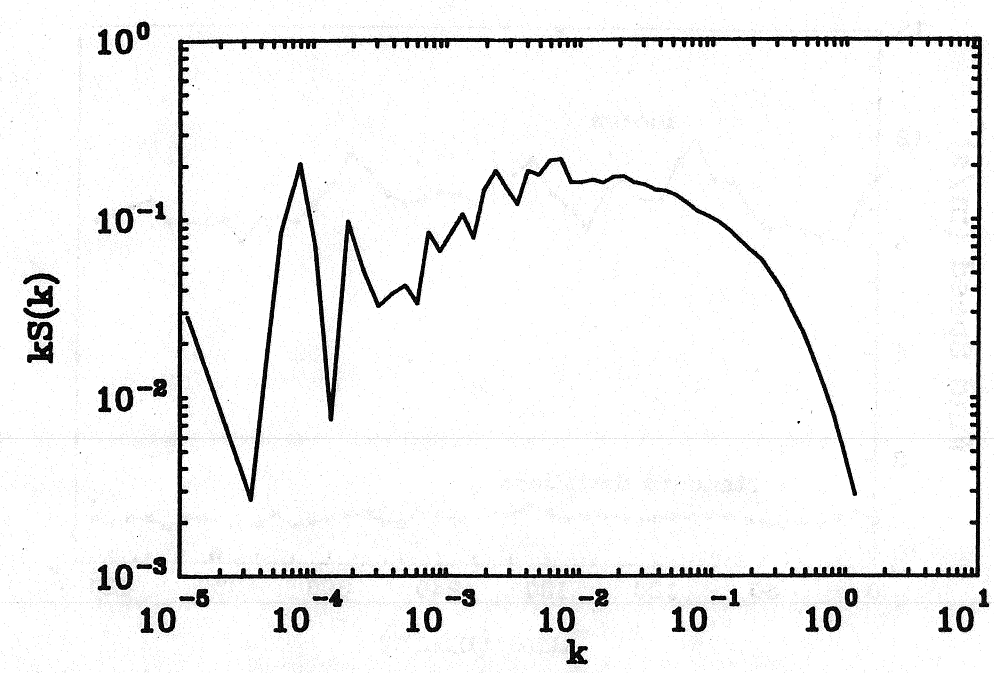

Figure 13: Power spectrum $kS(k)$ plotted against wave number $k = \frac{2\pi f}{U}$.

Spectral analysis

Power spectra and a complete set of coherence functions were calculated for the array of 16 cup anemometers. The power spectrum for the time series given previously (Fig. 11) is shown in Fig. 13. The fall-off in the upper end of the calculated spectrum is due to the limited response of the cup anemometer. Since all the cups were of the same type, it may be assumed that they have very similar response functions. Hence the effect of this fall-off on the coherence should be minimal. In any case, the coherence at high frequencies, except for very small displacements, is too low to measure.

With a time series of seven hours, the statistical degrees of freedom may be high without unduly compromising the frequency resolution. For all the coherence functions given here, 128 raw spectral estimates were used to calculate each point, giving a frequency increment of 0.0024 Hz. A number of coherence functions will now be presented, each being used to illustrate the main findings of the first experiment. In each case, the coherence is plotted using the dimensionless parameter $\frac{fD}{U}$.

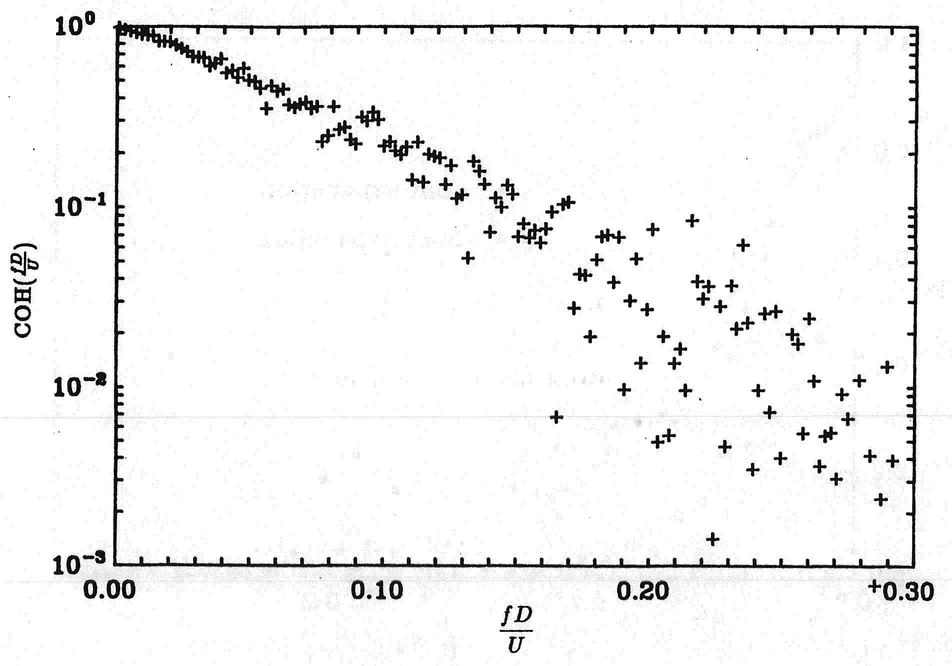

Figure 14: Lateral coherence for 5-m vertical separation.

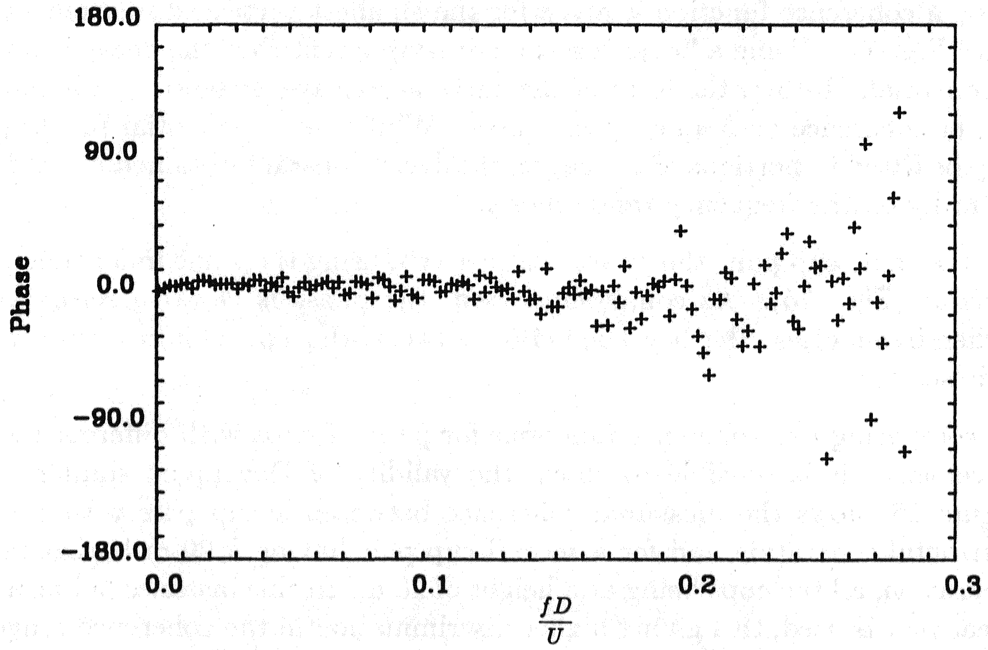

Figure 15: Phase for 5-m vertical separation.

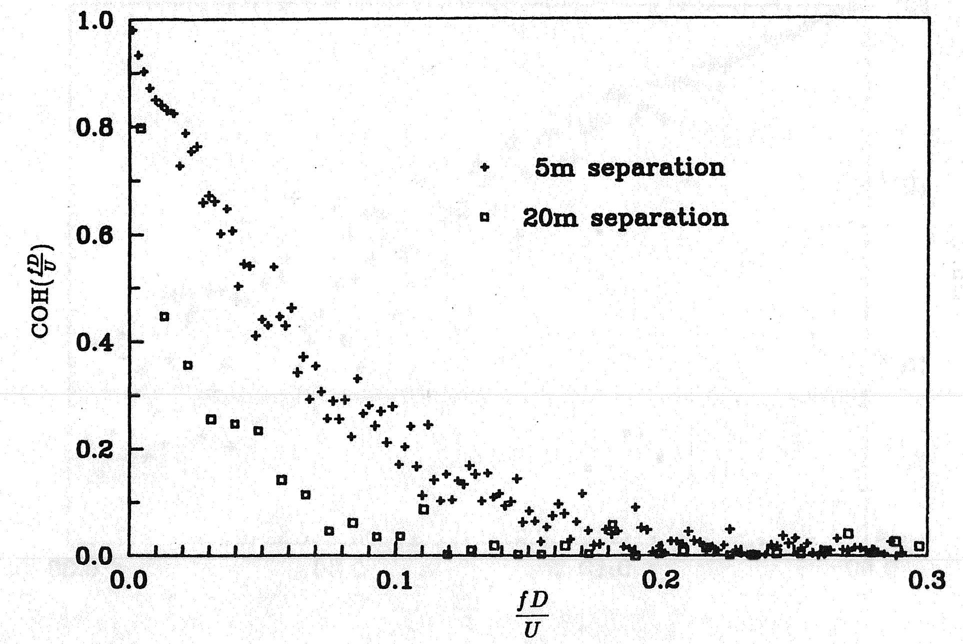

Figure 16: Lateral coherence for points with different horizontal separations.

Discussion of coherence results

First, a coherence function is given for the smallest vertical displacement, 5 m, (Fig. 14). Using a linear-log scale, it is apparent that the decay is not exponential. Rather, the form of the curve is concave, suggesting a higher loss of coherence as frequency increases. Whilst an exponential function may be fitted to portions of the curve, the decay constant obtained depends critically on the frequency range chosen.

For the same cup pair, the phase is also given, using the same independent variable (Fig. 15). As commonly found, the phase is close to zero. At higher frequencies, the low coherence between the two points results in wide scatter.

By comparing two coherence functions for pairs of cups with different displacements, it is possible to assess the validity of Davenport similarity. Figure 16 shows the measured coherence betweeen a cup pair with 5 m horizontal separation and for a second cup pair having a 20-m horizontal separation, all the cups being at a height of 20 m. In this instance, a linear-linear plot is used, this giving higher discrimination in the coherence range that may be reliably measured. For true similarity, the points from the two cup pairs should lie together. As can be seen, this is not the case.

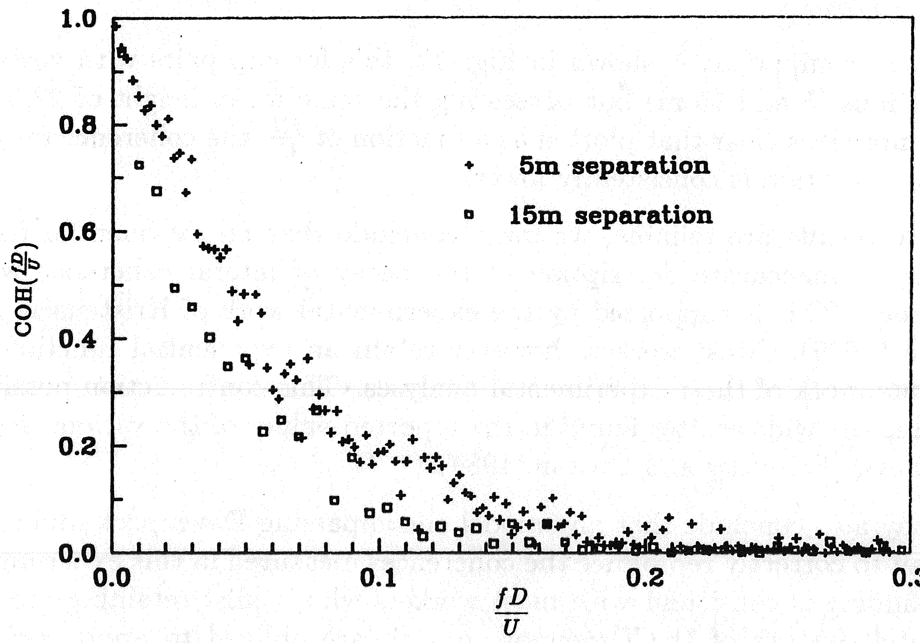

Figure 17: Lateral coherence for points with different vertical separations.

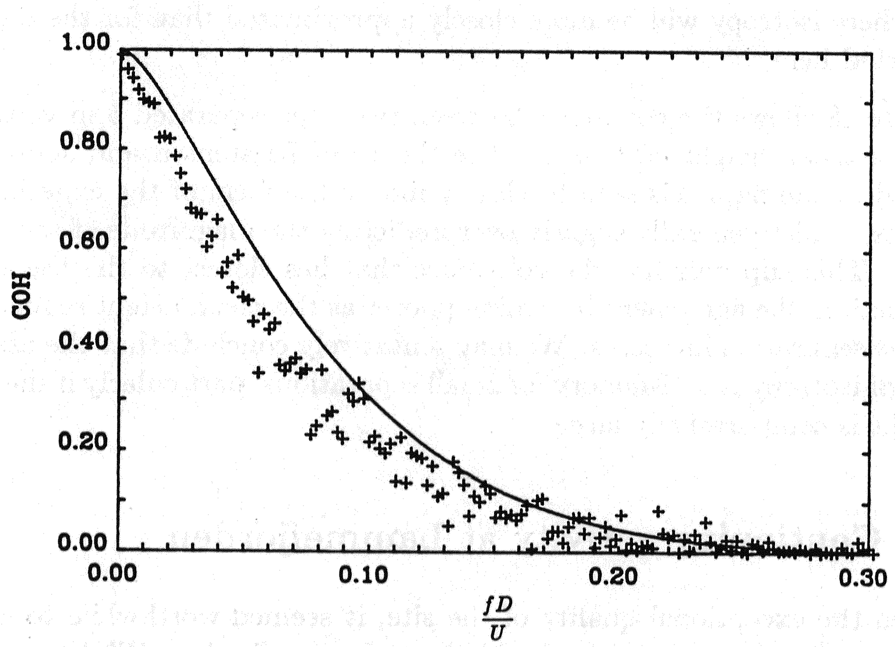

Figure 18: Lateral coherence for 5-m vertical separation. The solid line is the theory of Kristensen and Jensen (1979).

A second comparison is shown in Fig. 17, this for cup pairs with vertical separations (5 and 15 m) but possessing the same mean height of 22.5 m. Once more it is clear that plotted as a function of $\frac{fD}{U}$, the coherence for the larger separation is consistently lower.

If these results are reliable, we must conclude that an exponential function is an inaccurate description of the decay of lateral coherence with frequency. This is supported by the experimental work of Kristensen and Jensen (1979). Most workers however retain an exponential function as the framework of their experimental analyses. This contradiction possibly explains the wide scatter found in the reported values of the various decay constants, (Panofsky and Dutton, 1984).

We may also conclude that any model encompassing Davenport similarity will fail to correctly reproduce the coherences measured in this experiment. This finding is consistent with most workers who, whilst retaining the exponential feature of the Davenport model, are obliged to apply various corrections to the decay constant to account for height and separation.

The theoretical work of Kristensen and Jensen (1979) shows that the assumption of isotropy results in a model containing Davenport similarity. Indeed the experimental results given in their paper show good agreement in this respect. These are based on measurements made at a height of 60 m, where isotropy will be more closely approximated than for the data set reported here.

Figure 18 shows the coherence between two cups separated 5 m vertically, with a mean height of 32.5 m. The theory of Kristensen and Jensen, inserted in the figure, is seen to closely match the form of the experimental points, whilst generally slightly overpredicting the magnitude of the coherence. This cup pair has the coherence that lies closest to the theoretical prediction, the agreement becoming poorer as the mean height reduces and as the separation increases. We may tentatively conclude that the assumption of isotropy is satisfactory for small separations, particularly if the mean height is comparatively large.

3.4 Continuing activity at Lammefjorden

Given the exceptional quality of the site, it seemed worthwhile to extend the scope of the experimental activity at Lammefjorden. Whilst a certain amount of coherence data had already been gathered, further time series, in higher wind speeds or in different stratifications, would yield a comprehensive data set with which to verify a new coherence model.

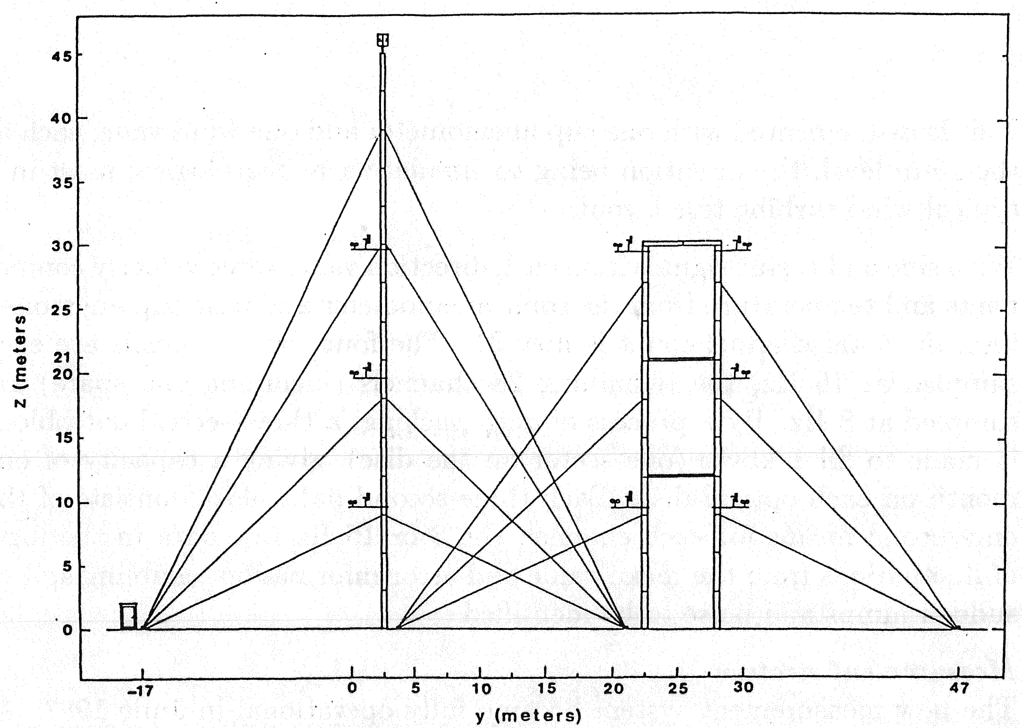

Figure 19: Instrument layout for the continuous measuring programme.

With the advent of optical disk storage technology, the effective limit to storage capacity available in the field has risen by perhaps two orders of magnitude. Various WORM (Write Once Read Many) devices are now commercially available, with capacities varying between 200 and 1000 Mbyte per drive. It is now technically feasible to sample and record high frequency wind data, without data reduction, for durations of months rather than hours.

Many uses, apart from coherence analysis, can be found for extremely long time series. Amongst these include the validation of flow and resource models, calculation of high resolution spectra and extreme statistics and the collection of extreme events (gusts). A data set of the type envisaged should also find applications in various other branches of atmospheric boundary layer research.

Description of the new measurement system

In the spring of 1987, a new measurement system was developed and installed at the Lammefjord site, based on a personal computer and a Gigadisc 1 Gbyte optical disk drive. At the same time, the instrumentation was altered, reducing the number of cup anemometers from 16 to 9 but installing a wind direction vane close to each cup. In addition, a sonic anemometer was mounted on the top of the 45-m mast.

A fourth, 10-m high mast was erected 15 m from the plane of the existing masts, in a direction that is upstream in the prevailing south-westerly wind.

This is instrumented with one cup anemometer and one wind vane, each at the 10-m level, the intention being to simulate a meteorological mast in a typical wind turbine test layout.

With sine and cosine signals from each direction vane, three velocity components and temperature from the sonic anemometer and nine cup anemometers, the total channel count is now 31. The four sonic channels are each sampled at 16 Hz, the remaining 28 channels (including one spare) are sampled at 8 Hz. By a process of data packing, a three-second data block is made to fill 1 kbyte (one sector on the disc), giving a capacity of one month on each optical disc. Each three-second data block consists of the one-second means for each channel, the 8 or 16 Hz raw data in the form of fluctuations from the mean value and error information, enabling spikes, sudden jumps and noise to be identified.

Measurement strategy
The new measurement system became fully operational in June 1987. At the time of writing (late September 87), close to three months of data have been obtained. Whilst the initial intention was to operate, as far as possible, without stopping, hardware faults and grid failures have resulted in a number of breaks in the recording. However, modifications to the software should result in greater resistance to transient faults and it is anticipated that in the remaining nine months of the experiment, fewer significant breaks will occur.

3.5 Conclusions

A complete description of atmospheric turbulence requires knowledge of both the temporal and spatial structure of the wind. Of particular importance to wind turbines is the lateral coherence of longitudinal velocity fluctuations, for which the Davenport empirical model is generally employed. An experiment using an array of fast responding cup anemometers spaced over a plane corresponding to a wind turbine rotor disc, has been conducted. It has been found that the exponential decay of coherence with frequency, inherent in the Davenport model, is not justified by the data. In addition, the concept of Davenport similarity, whereby the coherence function has only the argument $\frac{fD}{U}$, does not accord with the experimental results.

Using recently introduced optical disc storage technology, the original experiment has been extended, with the aim of collecting high temporal and spatial resolution data over the period of one year. This will yield vast amounts of wind data for application in many wind turbine related areas.

Initially, the data will be used for studying extreme events (gusts), for further coherence analysis and for verifying various flow and energy simulation models. The author welcomes suggestions as to other possible uses.

3.6 References

Davenport, A.G. (1961). The spectrum of Horizontal Gustiness Near the Ground in High Winds. *Quart. J. Roy. Met. Soc.*, **87**, 194-211.

Garrad, A.D. and Hassan, U. (1986). The dynamic response of wind turbines for fatigue life and extreme load prediction. Proceedings of the European Wind Energy Conference and Exhibition, Rome, October, Vol. I, 401-406.

Jensen, N.O. and Frandsen, S. (1978). Atmospheric turbulence in relation to wind generator design. Proceedings of the Second International Symposium on Wind Energy Systems, Amsterdam.

Kristensen, L. and Jensen, N.O. (1984). Lateral coherence in isotropic turbulence. *Boundary- Layer Meteorol.*, **17**, 353-373.

Kristensen, L. and Frandsen, S. (1982). Model for power spectra on the blade of a wind turbine measured from the moving frame of reference. *J. Wind Engineering and Industrial Aerodynamics*,**10**, 249-262.

Madsen, P.H. et al. (1984). Dynamics and fatigue damage of wind turbine rotors during steady operation. Risø report Risø-R-512.

Madsen, P.H. (1986). Simplified rotor loads from wind turbulence. Proceedings of the European Wind Energy Conference and Exhibition, Rome, October, Vol I, 377-382.

Panofsky, H.A. and Dutton, J.A. (1984). Atmospheric Turbulence. John Wiley & Sons, New York, 218-220.